Bottom Boundary Layer Processes Associated with Fine Sediment Accumulation: Application to STRATAFORM

Carl T. Friedrichs and L. Donelson Wright
School of Marine Science, Virginia Institute of Marine Science
The College of William and Mary, Gloucester Point, VA 23062-1346
phone: (804) 684-7303 fax: (804) 684-7195 email: cfried@vims.edu
phone: (804) 684-7103 fax: (804) 684-7097 email: wright@vims.edu
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LONG-TERM GOAL

The global objective of the Virginia Institute of Marine Science (VIMS) involvement in the STRATAFORM program is to improve understanding of the spatially and temporally varying mechanisms that suspend, transport, and deposit sediment on the continental shelf in the vicinity of the mouth of the Eel River specifically and generally on continental shelves that are accumulating fine sediment.

SCIENTIFIC OBJECTIVES

Specific objectives of VIMS involvement in STRATAFORM Phase I and II were to observationally characterize the spatial and temporal variability of bed roughness, bed stress, sediment resuspension and sediment flux at multiple sites on the Eel River shelf. Over the past year (October 1998-October 1999) our primary aim has been to synthesize our field results with other STRATAFORM investigators in order to help answer four of the six essential questions identified at the 1998 STRATAFORM Keystone meeting for Phase III of the program's shelf component: (1) How is sediment that is lost from the plume moved seaward to the mid-shelf mud deposit? (2) What are the magnitudes and mechanisms of storm- and flood generated sediment fluxes in the along-shelf direction? (3) How do flood deposits evolve in response to physical and biological reworking? (4) What is the "skill" of Eel shelf models in predicting relevant processes in other fine grained depositional systems?

APPROACH

Our approach in Phase I and II involved field observations of bed micromorphology, benthic flow, bed stress, suspended sediment concentration, and suspended sediment flux on the Northern California continental shelf north of the Eel River mouth. Over the late fall and winter of 1995 to 1996, we obtained regional measurements of bottom roughness via side-scan sonar and via profile and surface camera images of the sediment-water interface. We deployed fully-instrumented bottom boundary layer tripods on the “S” line at depths of 60 m and 70 m in January and February 1996, during which time two high energy events occurred. The tripods were re-deployed on the “G” line at depths of 30 m and 60 m from November 1996 to January 1997, a period that included a major flood event. Our approach in Phase III is to further develop and apply asymptotic analytical relations which highlight the most important mechanisms for fine sediment suspension, transport and deposition acting on the Eel River shelf. This approach will provide a conceptual bridge between environmental forcing and the output of more complex numerical models.

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WORK COMPLETED

Our field work as part of STRATAFORM Phase I and II has been completed. Initial analyses of the associated field data sets are also finished and the tripod data sets have been published as VIMS data reports (Wright et al. 1996a; Hepworth et al. 1997) and also on the VIMS STRATAFORM website: http://www.vims.edu/physical/strataf/strataform.htm. Analysis of bed micromorphology has been published as a Masters Thesis (Cutter 1997) and associated camera images are available on the web at http://www.vims.edu/~cutter/st95spi.html. Data reports, including data summaries on diskettes were prepared and distributed to interested STRATAFORM participants as soon as initial analyses and data quality assessments were completed. Some initial results from the first field experiment were reported by Wiberg et al. (1996). A paper detailing the results of the tripod measurements from the first VIMS field deployment has recently appeared in the STRATAFORM special issue of Marine Geology (Wright et al. 1999). A paper interpreting the micromorphology and biological alteration of the upper seabed observed during the first field experiment has been submitted to Continental Shelf Research (Cutter and Diaz Submitted). The ease with which our group made VIMS tripod data from this first deployment available to other investigators in STRATAFORM is illustrated by its preferential use in the initial calibration of numerical models by groups that did not include field specialists (Morehead and Syvitski 1999; Reed et al. 1999; Zhang et al. 1999). A paper detailing the results of the second VIMS field deployment has been accepted for publication in Continental Shelf Research (Friedrichs et al. Accepted). Our work in FY 1999 as part of STRATAFORM Phase III has been presented at Fall 1998 AGU (Friedrichs et al. 1998; Wright and Friedrichs 1998) and will soon be presented in Shanghai at the International Symposium of Sedimentological and Dynamic Processes in Estuaries and on Coasts (Wright et al. Accepted) and at Ocean Sciences 2000 AGU (Friedrichs et al. Submitted; Scully et al. Submitted; Wright et al. Submitted).

RESULTS

The results of our first field experiment (Wright et al. 1996b; Cutter 1997; Kim et al. 1998; Wright et al. 1999; Cutter and Diaz Submitted) include interpretation of bottom images and tripod time-series. Based on image data from December 1995, three regions along the “S” line were defined within water depths of 28 to 83 m: inshore shelf sands, a transitional region where sands transported by storms alternate with flood beds, and mid-shelf flood deposits. The number and type of biogenic features changed with changing sedimentary region. The degree of bioturbation was highest in the flood deposit region where burrows, the surface unconsolidated layer, active and relict feeding voids, and animals were more prevalent. In the transitional zone, there was evidence for both shallow and deep infaunal activity, but also apparently less utilization of the storm sand layer, suggesting that the infaunal community has adapted to the combined influence of deposition and storm transport. At the S60 and S70 tripod sites, biogenic roughness with ~ 2 cm relief prevailed.

Tripod data identified two high energy events between January and March 1996, with near-bed suspended sediment concentrations reaching 2 g/l at 60 m (15 cm above the bed) and 1 g/l at 70 m (27 cmab). At these times, suspended sediment induced stratification significantly suppressed near-bed turbulence. The abundance of under-consolidated fine sediment on the shelf to the north of the Eel River presumably allows increases in stress to be accompanied by progressive increases in suspended sediment concentration within the log layer, causing the gradient Richardson number to remain near the critical value of 1/4. This contrasts to situations where bed armoring limits the total amount of fine sediment in suspension. Depth-integrated across-shelf suspended sediment fluxes were seaward at 60 m and near zero to weakly landward at 70 m during high-energy periods, implying flux convergence. This is consistent with the conclusions of other STRATAFORM investigators that rapid long-term accumulation of mud is occurring on the mid-shelf.

From our analyses of our second field experiment (Friedrichs et al. 1998; Wright et al. 1998; Friedrichs et al. Accepted), we observed a significant, but indirect contribution to bottom boundary layer processes to have been made by the Eel River flood plume. A major flood of the Eel River that peaked on January 1, 1997 distinguished the 1996-1997 field period. During the latter half of the storm event associated with the flood, shelf currents shifted to the south and a high concentration event was observed at G65. This event contained fine sediment advected from the north and originally discharged during the flood. Wave agitation of the bed was strong during the first part of the high-turbidity event but weak thereafter. Distinctively different velocity and turbidity profiles prevailed during the “strong-wave” and “weak-wave” phases of the event.

As part of our Phase III work, we have performed a comparative analysis of bottom-boundary-layer velocity profiles, bed stresses and suspended sediment concentration profiles that we have measured with instrumented tripods in four contrasting shelf and semi-enclosed bay environments that are presently accumulating fine sediments (Wright et al. 1998; Friedrichs et al. Accepted). The sites are: the northern California shelf off the mouth of the Eel river; Eckernförde Bay, southern Baltic Sea; the York River estuary, lower Chesapeake Bay; and the Louisiana shelf to the west of the Mississippi River mouth. At these sites, the presence of density stratification caused simple fits of log profiles to velocity observations over the lowest meter to overestimate bottom stress. Observed semi-log velocity profiles were (1) concave downward, (2) straight, or (3) concave upward depending on whether the density anomaly decreased with height above the bed (1) much more slowly than, (2) at roughly the same rate as, or (3) much more rapidly than z^{-1}. Stable stratification was attributable to a combination of suspended sediment and thermohaline effects, with the former and latter dominating under high and low energy conditions, respectively. At all sites, the near-bed gradient Richardson number approached or exceeded the critical value of 1/4 implying that turbulence was damped by stable stratification. Results point to the likelihood that stable near bed stratification, which is often associated with fine sediment accumulation plays an important role in accelerating accumulation by reducing near bed turbulence.

As part of our Phase III work we have also developed asymptotic analytical relations for critically stratified bottom boundary layers (Friedrichs et al. 1998, Submitted), as we observed on the Eel River shelf. When strong waves suspend abundant, easily eroded fine sediment to concentrations approaching fluid mud within the wave boundary layer, the concentration gradient at the top of the wave boundary layer becomes sufficient to suppress turbulence to the point that the gradient Richardson number is maintained near its critical value of 1/4 within the overlying current boundary layer. The resulting velocity profiles within the current boundary layer are very nearly logarithmic even though the Karman-Prandtl equation no longer applies. We have developed a simple analytical theory to derive mean current stress and sediment flux from such velocity profiles without requiring any information regarding sediment properties (Figure 1). This theory also suggests that relatively sparse observations of velocity and/or concentration within the constant stress layer can be used to remotely infer both the concentration and down-slope velocity of gravity flows within the wave boundary layer. Coupling of conditions within the wave boundary layer and constant stress layer also suggests that the suspended sediment concentration within the wave boundary layer may control the wave-averaged stress and current speed within the overlying "log-layer".

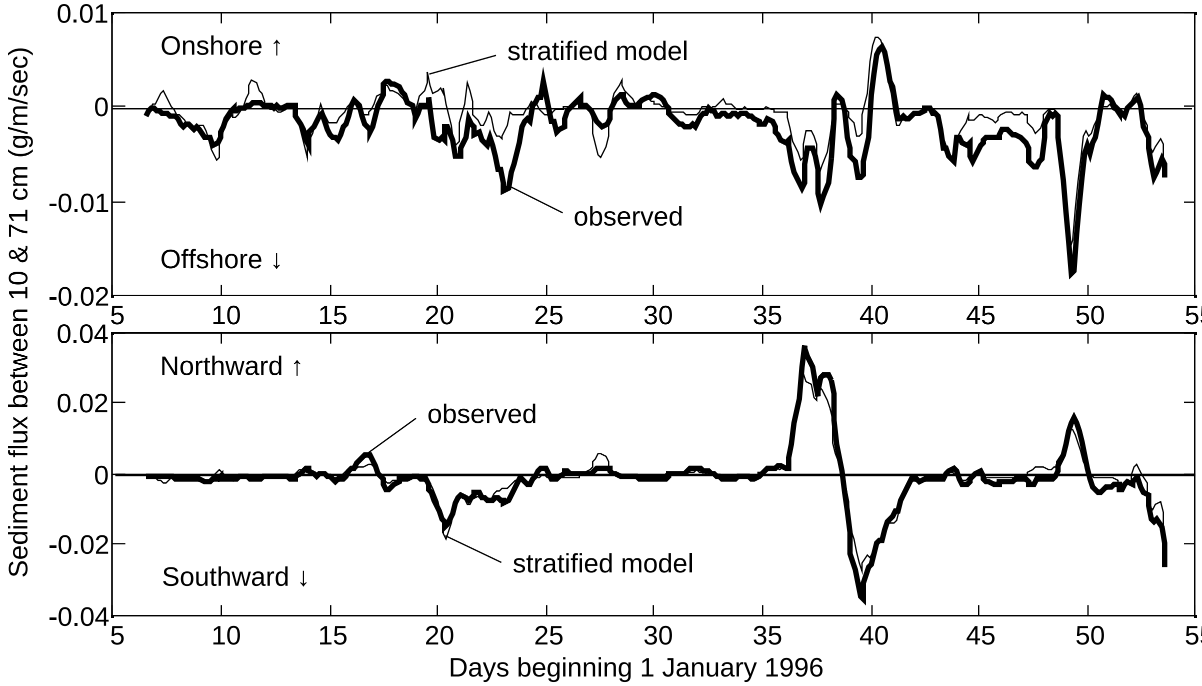

Figure 1. Comparison of observed sediment flux to that modeled from velocity profile alone.

Most recently, our Phase III work has focused on the role of hyperpycnal plumes in shelf sediment transport (Wright et al. 1999, Submitted; Scully et al. Submitted). Field observations from several shelf environments in which we have worked show that hyperpycnal plumes may constitute an important mode of fine sediment transport across and along continental shelves. On the northern California shelf off the Eel River, in the Gulf of Bohai off the Yellow River, and on the Louisiana shelf to the west of the Mississippi River, we often observed near bed sediment concentration to be influenced by the horizontal advection of near-bottom turbid layers a meter or more thick. Advection of the layers reflected a combination of forcing by wind and tide generated currents and gravity-driven down-slope movement. In the cases examined, downslope movement of hyperpycnal layers was pulsational and occurred when the eddy viscosity induced in the bottom boundary layer by waves and other currents was temporarily relaxed. Autosuspending, gravity-induced turbidity currents were not observed in any of the cases.

IMPACT/APPLICATIONS

Measurements of near-bottom processes at different depths on the shelf provide insights into the mechanisms responsible for along-shelf and across-shelf sediment suspension and transport, the sources and nature of across-shelf variations in bottom stress and hydraulic roughness, and the causes and magnitudes of the across-shelf gradients in sediment flux that may contribute to sediment deposition. The results from the STRATAFORM site, when compared with other sites that are accumulating fine sediment, have yielded new generic insights concerning differences between bottom boundary layer processes in such environments and those that prevail on sandy shelves. Two of the marked differences highlighted to date by our results are the important role of suspended sediment in suppressing turbulence on shelves accumulating fine sediment and the significant role of hyperpycnal plumes in modifying the nature of across-shelf sediment flux. Our results are being applied to develop modified models for transport of highly concentrated fine sediment over soft, easily eroded beds.

TRANSITIONS

Our data on bed stresses and resulting sediment resuspension have been made available to modelers and other STRATAFORM investigators and are being used to verify bottom boundary layer and sediment transport models. Our data can easily be accessed via data reports (which include data summaries on diskettes) and via the VIMS STRATAFORM website. Published papers by others which have directly utilized VIMS data include Morehead and Syvitski (1999), Ogston et al. (1999), Reed et al. (1999) and Zhang et al. (1999). Several additional papers by non-VIMS authors incorporating VIMS data are in preparation.

RELATED PROJECTS

The following projects involving Friedrichs and/or Wright also address fine sediment transport and accumulation in coastal environments:

1. Biological Mediation of Bottom Boundary Layer Processes and Sediment Transport in Estuaries. Office of Naval Research (Harbor Processes).

2. Physical and Biological Mechanisms Influencing the Development and Evolution of Sedimentary Structure. Naval Research Laboratory (Coastal Benthic Boundary Layer SRP).

3. Sediment Dynamics of a Microtidal Partially-Mixed Estuary. Submitted to National Science Foundation (Marine Geology and Geophysics).

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